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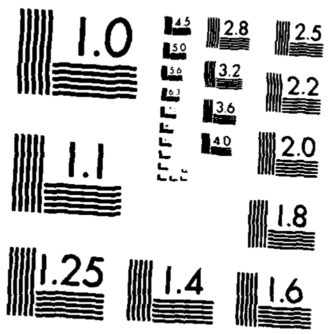

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SUMMARY

The Subjective Transfer Function (STF) method for modeling systems solves the problem of credibly incorporating human judgments into computer models. By employing hypothesis testing principles, expert judgments are represented in algebraic functions that derive from tested theories. The testability feature stems from the algebraic approach to subjective measurement. The STF method provides additional features necessary for coalescing judgments obtained from different groups of system experts into an overall perceptual outcome. The paper describes the STF method and how STF models are used to analyze command and control systems.

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INTRODUCTION

Computer modeling and simulation is a powerful technique for systems analysis; however, its potential for analysis of command and control systems has yet to be realized. In fact, for analyzing any system that includes physical (e.g., equipment, facilities, weapon systems), soft (e.g., procedures, information) and human (e.g., assessment, decisionmaking) elements, a major modeling problem has been to determine functional relationships that represent the processes by which these elements produce system outcomes. Human judgments usually provide the only or best way to capture the essence of the functional relationships, but the problem is to model the human judgments in a credible way.

The Subjective Transfer Function (STF) method [1,2] was developed to solve the judgment modeling credibility problem by employing the scientific principle of hypothesis testing. This principle stems from the algebraic modeling approach to subjective measurement [3-10] where meaningful subjective scale values derive from tested theories. The STF method provides additional features necessary for coalescing judgments obtained from different groups of system experts into an overall perceptual outcome.

In the STF method, a system is divided into units corresponding to tasks performed. Factors and outcomes describing each unit are identified in conjunction with the appropriate body of task experts. Outcome judgments are collected from the experts using experimental designs that allow causal hypotheses about effects of the factors on judged outcomes to be *tested*, and thus rejected if they are not supported by the judgment data. Hypotheses are in the form of algebraic functions that specify these effects. The appropriate algebraic functions (STFs) that describe the interrelationships between factors and outcomes in each unit interlink to form the STF model. The model is used to predict outcomes under different conditions described by different system capabilities.

The STF method can be used to provide complete system models, or partial models for incorporation in computer models including more traditional deterministic and stochastic functional representations.

Recent applications of the STF method have included modeling and evaluating USAF air defense command and control (C2) systems [12], USAF air offense C2 systems [13], NATO air defense situation assessment and engagement decisionmaking C2 systems [14], and USN special warfare operations.

AN EXAMPLE PROBLEM

We will use an example problem to describe the principles and procedures of the STF method. Suppose we wanted to evaluate C2 system designs with respect to their effect on the targeteer's ability to identify the important targets in the enemy's second echelon. The first step is to determine the outcome(s) that reflects target identification capability and the factors that cause the outcome(s). Figure 1 depicts a simplified representation of this problem where the target identification outcome has been determined to be "the percent of important enemy second echelon targets that could be identified" and there are three causal factors that affect that outcome--Enemy Vehicle Information (the percent of the enemy vehicles that are observed and reported to the targeteer), Enemy Emitter Information (the percent of the enemy emitters that are observed and reported to the targeteer), and C2 Processing Capability (how the vehicle and emitter information is processed by the targeteer).

Target Identification (% of important enemy targets that could be identified) — **Judged Outcome**

STF

Enemy Vehicle Information (% Observed)	Enemy Emitter Information (% Observed)	C2 Processing Capability
90%	90%	Computer Display & Interpretation
60%	60%	Computer Display Human Interprets
30%	30%	Greaseboards and Maps
10%	10%	

Fig. 1 - Example Problem

In the STF method, each causal factor has a set of *levels* that describe the points along the factor dimension. In Fig. 1 the levels are shown under the factors. The endpoints of each set of quantitative levels (e.g., 10-90%) reflect the range of capabilities of interest. The qualitative levels such as used for Processing Capability specify the capabilities of interest. Levels should be selected to span the capabilities of interest, perhaps from those that currently exist to those associated with possible system enhancements. These factor levels are manipulated in experimental designs (described in the next section) that permit tests among unique predictions of hypothesized algebraic functions (STFs) that specify the cause and effect relationship among factors and outcomes.

In a complex system, there are many experimental units such as the one shown in Fig. 1. The STFs serve to link the units together and to an overall system outcome. Next, we describe experimental design characteristics that we employ to determine appropriate STFs.

STF EXPERIMENTAL PROCEDURES AND DATA ANALYSES

Experimental designs permit tests among predictions of hypothesized algebraic functions. Questionnaire items generated by the experimental designs are compiled in questionnaire format and fielded to the defined expert respondent population. The data are then analyzed to determine the appropriate STFs for each unit in the structure. Functions accepted as appropriate become the STFs in the model.

Experimental Design

To illustrate the idea of *testing* among functions' predictions we will use four algebraic functions--additive, relative-weight averaging, multiplicative, and range.

The algebraic formulation for an *additive* function in the three factors shown in Fig. 1--Enemy Vehicle Information (V), Enemy Emitter Information (E), and C2 Processing Capability (P)--is

$$r = s_{V_i} + s_{E_j} + s_{P_k}, \qquad (1)$$

where the response, r, is the simple sum of the scale values (s) associated with the ith, jth, and kth levels of factors V, E, and P, respectively.

The algebraic formulation of a *relative-weight averaging* function is

$$r = \frac{w_0 s_0 + w_V s_{V_i} + w_E s_{E_j} + w_P s_{P_k}}{w_0 + w_V + w_E + w_P}, \qquad (2)$$

where $w_0 s_0$ are the weight and scale value associated with the initial impression (what the response would be in the absence of specific information, w_V, w_E, and w_P are the weights associated with the factors V, E, and P, respectively, and r and s are as described above.

A *multiplicative* function can be written

$$r = s_{V_i} s_{E_j} s_{P_k}, \qquad (3)$$

where the terms are as described above.

A *range* function can be written

$$r = \frac{w_O s_O + w_V s_{V_i} + w_E s_{E_j} + w_P s_{P_k}}{w_O + w_V + w_E + w_P} + \omega(s_{MAX} - s_{MIN}), \qquad (4)$$

where s_{MAX} and s_{MIN} are the subjective maximum and minimum pieces of information contained in an item, and ω is a weighting parameter for the range term.

These four functions fall into two major classes. Equations 1 and 2 are noninteractive functions; Eqs. 3 and 4 are interactive functions. All four functions make *different* predictions with respect to the pattern data points should follow when experimental designs use factorial combinations of stimuli that vary the amount of information in a questionnaire item. First, we describe a factorial experimental design that varies the amount of information and then we describe the different predictions.

An experimental design that allows tests among the four functions specified above is diagrammed in Fig. 2. The larger three-way factorial design crosses each level of each factor shown in Fig. 1, producing 48 cells. Each cell in the design is translated into a questionnaire item. Each item contains one level of each of the three factors and thus

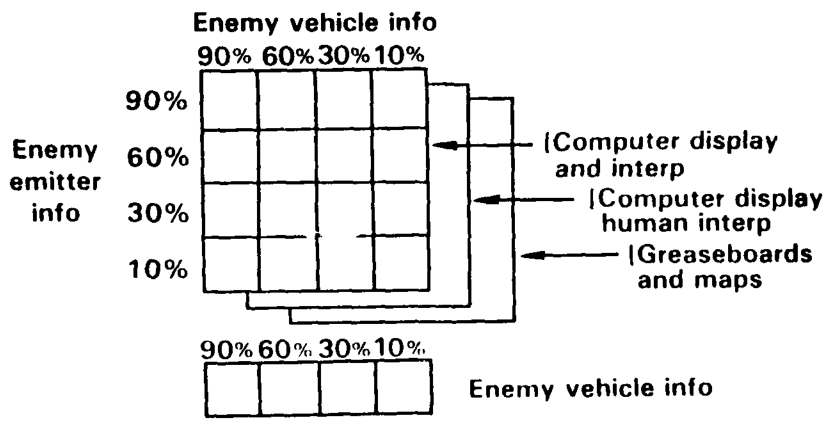

Fig. 2 -- Experimental Design Example

contains three pieces of information. For example, one item would describe the targeteers as receiving 90% of the enemy emitter information, 60% of the enemy vehicle information, and as displaying information using greaseboards and maps. The one-way design shown below the three-way design uses all levels of the enemy vehicle information factor, producing four questionnaire items each containing one piece of information (the percent of enemy vehicles that are observed and reported to the targeteer). The two designs taken together would produce a questionnaire with 52 items.

One could add more factorial combinations for more stringent tests among functions' predictions. A complete design of the factors shown in Fig. 1 that varies the amount of information would also include the other two one-way designs and the three possible two-way designs.

Experimental Procedures

Questionnaires are administered to a defined expert respondent population. These are people who perform, have performed, or are training to perform the task (the latter group is the typical population when dealing with wartime scenarios). Respondents' judgments are in operational terms. For example, to each of the 52 items that would be produced from the design just described, respondents might be asked to judge the percent of the important enemy targets they think they could identify.

Before respondents fill out questionnaires, factor definitions and background scenario (e.g., war situation) are discussed. In this discussion, respondents are asked to place themselves in the described situation and to imagine performing their tasks under the conditions described by the factor levels. The many characteristics of the situation not described by the items are "filled in" by the respondents who are experienced in the environment. This extends to experimental factors when they are not included in the item (as with the one-way design shown in Fig. 2). After discussing the factors and background scenario, respondents take a warm-up questionnaire of about 20 representative items to familiarize themselves with the questionnaire format and the response scale. They then take the questionnaire.

Data Analyses

Two types of analyses are used to test functions: graphic and least-squares. Graphic analyses aid in cutting down the number of viable STFs and in diagnosing systematic trends in the data. The graphs of hypothetical data shown in Fig. 3 help to illustrate how graphs are used in data analyses. In Fig. 3, mean response is plotted as a function of the levels of the enemy vehicle information factor with a separate curve for each level of the processing capability factor. If the judgment data obtained from the three-way design shown in Fig. 2 revealed a divergent interaction (such as the one shown in Fig. 3) for all pairs of factors, all noninteractive functions would be rejected. If data from the three-way design revealed parallel curves for all pairs

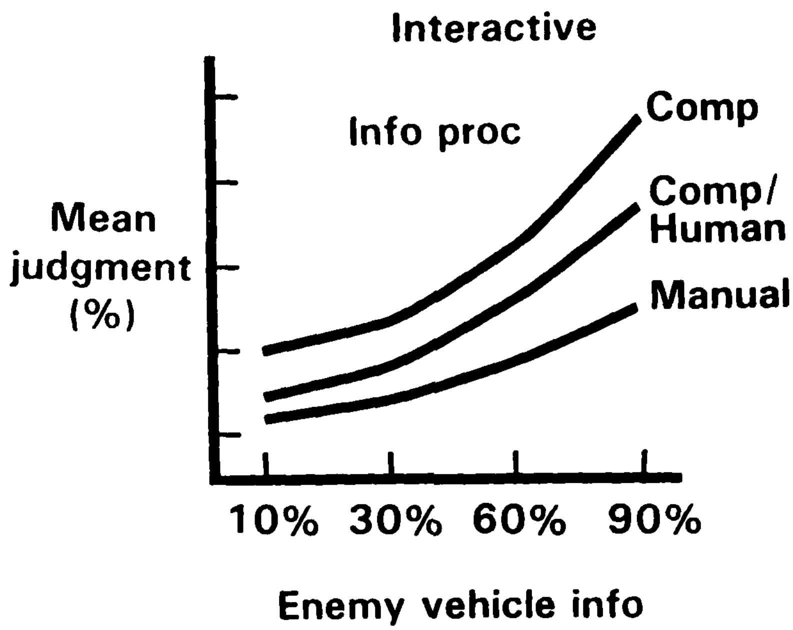

Fig. 3 -- Hypothetical data plot

factors all interactive functions would be rejected.

Once the interactive or noninteractive class is recognized, the one-way design data is used to distinguish between particular functions in the appropriate class. For example, let's say the data revealed parallel curves in support of a noninteractive function. Both the additive and averaging functions (Eqs. 1 and 2) fall in this class. However, the averaging model predicts that the slope of the line obtained from the one-way design data should be *greater* than the slopes of the curves from the three-way design. On the other hand, an additive model predicts that this slope should be the same. These predictions can be seen from the algebraic formulations of the functions. For the averaging function, when there is one piece of information (e.g., Enemy Vehicle Info.), the judgment should follow the form

$$r = \frac{w_0 s_0 + w_V s_V}{w_0 + w_V}$$

However, when there are three pieces of information, the judgment should follow the form

$$r = \frac{w_0 s_0 + w_V s_V + w_E s_E + w_P s_P}{w_0 + w_V + w_E + w_P} .$$

The denominator of the second expression is larger than that of the first, making the slope of the line for Enemy Vehicles with three pieces of information,

$$\frac{w_V}{w_O + w_V + w_E + w_P},$$

smaller. By the same reasoning, the slope of the lines under an adding model should be the same, independent of the *amount* of information contained in the item. Thus, the two noninteractive functions make different predictions when experimental designs vary the amount of information contained in the items.

The multiplicative and range interactive functions (Eqs. 3 and 4) make similar different predictions with respect to the pattern of data points when the experimental design is factorial and varies the amount of information. Both functions predict that interactions should occur. Both functions also predict that most of the interaction should be in the bilinear component.[1] However, the range function like the relative-weight averaging function predicts that data from a one-way design should produce a steeper slope than data from a two or three way design, while a multiplicative function predicts that data from a one-way design should "fit into" the family of interactive curves produced from the three-way design.

These predictions are graphically illustrated in Fig. 4. The divergent curves indicate the class of interactive functions. If the one-way design data produced the dotted line shown in Fig. 4, it would support the predictions of a range function. If the one-way design data produced the dashed line, it would support the predictions of a multiplicative function.

Of course it could be the case in a three-factor design, that combinations of the trends predicted by Eqs. 1-4 are observed in the data. For example, two factors could combine multiplicatively with each other but additively with the third factor. Possible combinations of algebraic functions increase with the number of factors included in the design. Graphic analyses help to cut down on the number of possible STFs as explanations of a data set. Combinations that predict trends not found in the data are rejected as appropriate explanations of the judgments.

Once initial graphic analyses have limited the number of possible STFs to a select few, least-squares assessments of how well functions account for the data are made using a function-fitting program developed primarily at Rand that uses the STEPIT subroutine.[11] The idea is to select a function that has a low least-squares discrepancy *and* captures the unique data patterns found in the data. Assessments of how well

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[1] That is, every row (or column) plotted against every other row (or column) in the factorial design should yield a linear line.

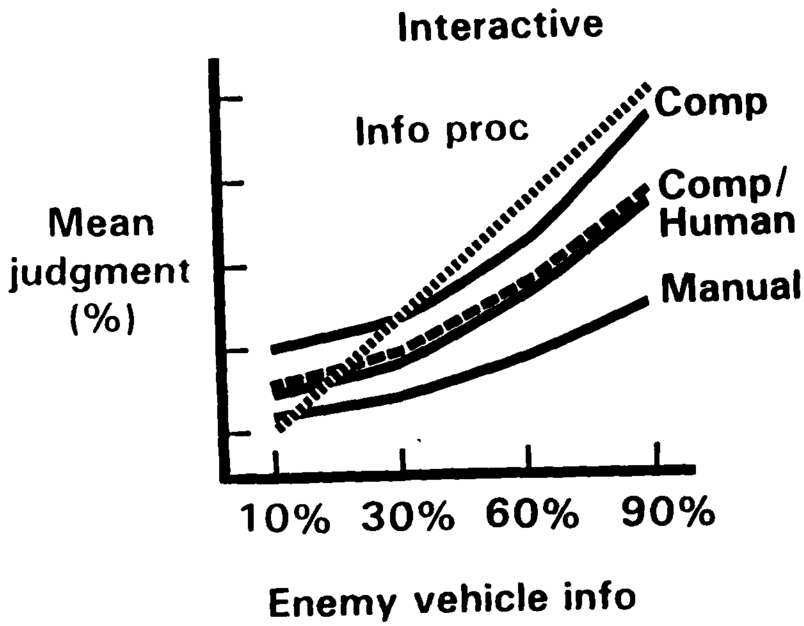

Fig. 4 -- Hypothetical one-way data plot

functions account for unique data patterns are made by looking at predicted and obtained graphs that plot both obtained and predicted responses (from the function) on the y-axis as a function of one factor in the design; a separate curve would be plotted for each level of another factor for predicted responses and asterisks could be plotted for obtained data. Goodness-of-fit assessments are made by where the asterisks fall relative to the predicted curves. If deviations are systematic (for example, curves are divergent but asterisks are systematically more divergent), the function being tested would be rejected in favor of one that accounted for the more extreme divergent pattern. Generally, a function that captures these unique data patterns also has the best least-squares fit. Of course, it is possible that all hypothesized functions might have to be rejected.

The examples and discussion just presented illustrate the *testability* feature of the STF method. When functions' predictions undergo stringent tests, functions that are retained as STFs have credibility as explanations of the judgment data.

STF MODELS OF COMPLEX SYSTEMS

In most applications of practical interest, the systems that are modeled contain many factors and outcomes. They are easily represented in a hierarchical structure with the outcomes from one tier forming causal factors at the next higher tier. Figure 5 is an example of a C2 model that we developed for the immediate targeting function of a Tactical Air Control Center (TACC) where targets are identified and aircraft are either launched from an alert status or diverted in the air from another mission to engage the target.[13] In this model, Target Identification is the *outcome* from a lower tier and is a *causal factor* affecting how well the immediate targeting function can be performed. Two groups of experts participated--targeteers for the target identification experiments and current operations officers for the immediate targeting experiments.

The STFs indicate interaction among all but one set of factors. The (+) or (-) signifies the range function has a positive or negative ω, respectively. A positive ω reflects a convergent interaction among the factors indicating, for example, that the better the enemy vehicle information, the *less* the contribution made by having better enemy emitter information (a result that is intuitively satisfying in this case). A negative ω reflects a divergent interaction and a corresponding opposite interpretation (the better one factor, the

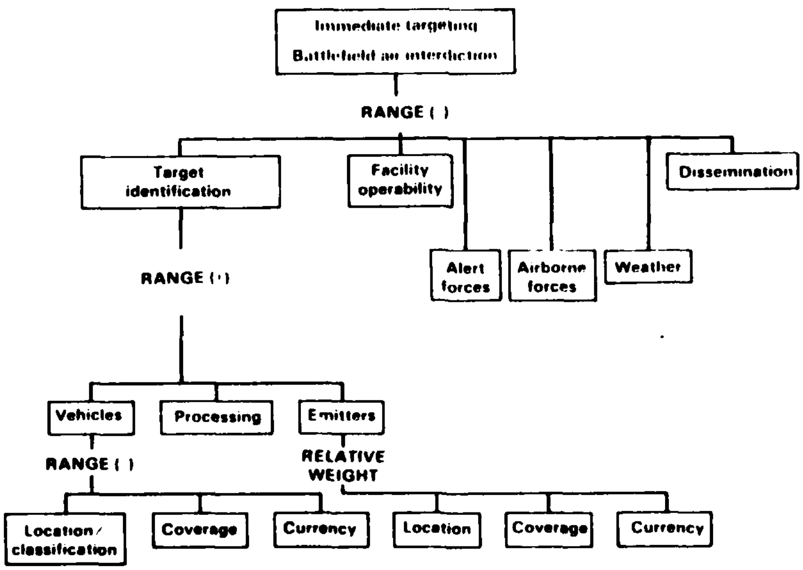

Fig. 5 -- Immediate targeting of second echelon forces

greater the contribution of another factor).

We selected a small STF model for illustration in this paper but we have developed more complex models using the method. The largest STF model to date is a model of an air defense C2 system that contains 96 factors and 25 outcomes, and included judgments from nine different groups of air defense C2 experts.[12]

SYSTEM EVALUATION WITH STF MODELS

Once an STF model is determined, it provides the means to predict system outcomes under a variety of situations. These predictions can be used to evaluate the effectiveness of a specific system, assess how changes to the system affect its effectiveness, and identify system features that can be modified to achieve desired effectiveness levels. In this section we explain how to use the model and present some example results.

Using the Model

To use the model to predict outcomes for a particular system, it is necessary to describe the capabilities of that system and the operational situation under which it is to be evaluated. System capabilities are described by specifying a factor level for each factor that represents a system capability. For example, the factor levels for target identification are shown in Fig. 6 and two sets of system capabilities (hence, two different systems) are specified in Table 1. For many STF models, an operational situation is described by specifying a factor level for each factor that represents a characteristic of the operational situation (e.g., number of missions, threat, and terrain). In this way, any combination of capabilities can be evaluated in any operational situation.

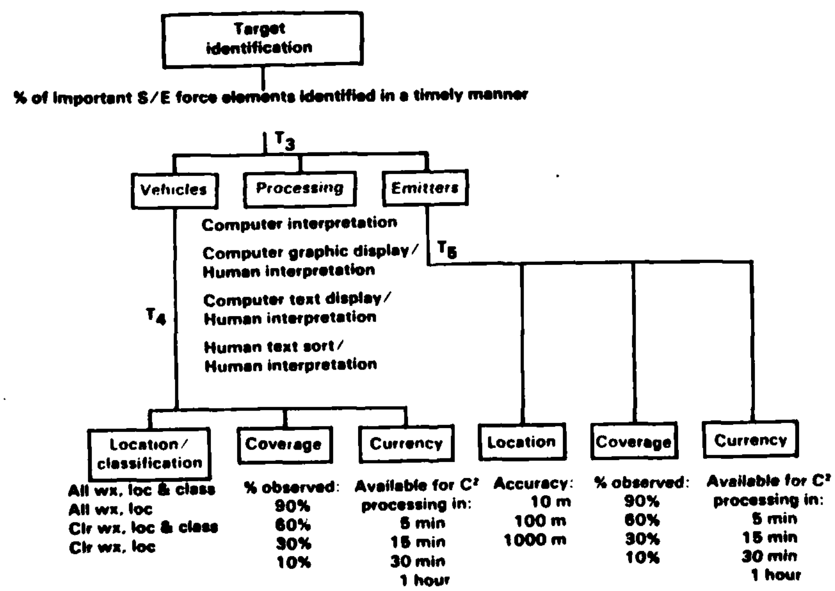

Fig. 6 -- Target Identification factor levels

Table 1

TARGET IDENTIFICATION C2 SYSTEMS

Factors	Baseline System (Factor Levels)	Enhanced System (Factor Levels)
Vehicle:		
Location and Classification	Clear Wx/ Loc only	All Wx/Loc & classify
Coverage	40%	80%
Currency	30 min	5 min
Emitter:		
Location	100 m	50 m
Coverage	60%	90%
Currency	1 hour	5 min
Processing	Human	Graphic/ Human
Outcome (% identified)	33%	68%

When factor levels are numbers, any quantity between the lowest and highest factor level used in developing the model can be specified. For example, emitter location accuracy factor levels of 10m, 100m, and 1000m were used in developing the model (Fig. 6). Hence, any accuracy from 10m to 1000m can be used in running the model. When factor levels are descriptive (e.g., processing factor levels in Fig. 6) only the descriptions used in the model development can be used.

The factor levels that describe the system capabilities and operational situation of interest are the inputs to the model.[1] The model uses them to calculate the functions and obtain the predicted C2 system outcomes.

[1] A general program to run STF models is available at Rand that can be run on any digital computer having a FORTRAN IV level compiler.

To investigate the effect of enhancements to a specific system, simply change the factor levels that are affected by that enhancement. For example, a system enhancement that increased coverage from 40% to 80% would be reflected by changing the coverage factor level from 40% to 80%.

Example Immediate Targeting Results

Using the STF model shown in Fig. 5, we investigated the effect on target identification and immediate targeting that could be realized by C2 system enhancements. We first described a "notional" baseline system that reflected capabilities typically fielded in existing tactical air C2 systems. We then described C2 system capabilities that could be realized by fielding selected new technology.

The results for target identification are shown in Table 1. The enhanced system included automating the sensor data processing and fielding highly capable intelligence collection systems. A dramatic improvement from 33% to 68% of the important targets identified is predicted by the model, implying a high payoff from incorporating the new technology.

The results for immediate targeting are shown in Table 2. The enhanced system includes only adding an improved airborne radar and communication capability (such as the AWACS). We readily see that the model predicts very little improvement (only 4%-6%) in the overall immediate targeting result from the extensive new sensing and processing upgrades. In fact, it is less than if the airborne radar and communications capability were improved (11%-13%). Such a result would lead C2 system managers to consider the latter improvement over the former, particularly if there was a cost advantage. One explanation for this non-intuitive result is that a "target rich" environment will exist and identifying sufficient targets to utilize the available friendly fighter forces is not a problem.

Table 2

IMMEDIATE TARGETING C2 SYSTEMS

Factors	Factor Levels: Baseline System	Factor Levels: Enhanced System
Facility Operability	60%	60%
Alert Force Access	60%	90%
Airborne Force Access	30%	90%
Weather Currency	3 hours	3 hours
Timely Order Dissemination	60%	90%
Target Identification	33%/68%	33%/68%
Outcome (opportunities exploited)	48%/52%	59%/65%

CONCLUDING REMARKS

In sum, the STF method can be used to construct models of systems where human judgments are the easiest, most practical, or most appropriate input to the model. STF models can be of the complete system or just part of the system. The advantage of the method is that the functions (STFs) that comprise the model are based on tested premises. Thus, conclusions about what affects system outcomes are credible.

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